

Gauged Axions and their QCD Interactions

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Abstract. We present a brief overview of axion models associated to anomalous abelian (gauge) symmetries, discussing their main phenomenological features. Among these, the mechanism of vacuum misalignment introduced at the QCD and at the electroweak phase transitions, with the appearance of periodic potentials, responsible for the generation of a mass for these types of axions.

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INTRODUCTION

Axions were introduced in 1977 by Peccei and Quinn (PQ) as an attempt to solve the strong CP problem, which finds its origin in the smallness of the QCD θ angle, as the measurements of the electric dipole moment of the neutron confirm. The invisible axion, which emerged from a modification of the original PQ proposal, is expected to play a considerable role in cosmology, since it could be a significant component of cold dark matter (see [1]). For this reason they have been at the center of a large number of investigations, in an attempt to identify possible ways of experimental detection of these particles.

The generation of a PQ axion follows a well-established theoretical pattern, characterized by the breaking of a global $U(1)_{PQ}$ symmetry at a very large scale f_a (about 10^{12} GeV), followed by a tilting of the PQ potential, associated to this symmetry, and taking place at the quark-hadron transition. The mass of the axion (m_a) is indeed defined in terms of the two scales which characterize the first breaking (f_a) and the tilting (Λ_{QCD}) as $m_a \sim \Lambda_{QCD}^4/f_a^2$. The “extra potential” which causes the tilting of the PQ mexican-hat is attributed to QCD instantons. It is periodic, with a period given by πf_a and a strength which is of the order of Λ_{QCD} . We just recall that an axion undergoes a global shift ($\theta \rightarrow \theta + \alpha$) under a global $U(1)_{PQ}$ transformation, with α denoting the gauge parameter. For a gauged axion α is promoted to a local parameter.

There have been several attempts to modify the standard PQ picture, mostly for cosmological reasons, for instance to provide a possible explanation of the dark energy problem, by introducing a global $U(1)$ symmetry broken at a very large scale as in PQ, but with a tilting occurring at the electroweak scale (see for instance [2]). In this case one needs to construct an anomalous (global) $U(1)$ symmetry characterized by a mixed anomaly just with the electroweak sector. Also in this case the axion, which remains a Nambu-Goldstone mode until a tilting in the broken original potential takes place, acquires a small mass. In the electroweak case, however, this turns out to be much

smaller than the one obtained in the standard QCD scenario, due to the far smaller size of the “extra potential”, which is due to electroweak instantons, compared to the QCD case.

As we extend the theory and require the gauging of the anomalous $U(1)$ symmetry, the gauge invariance of the effective action requires the presence of local counterterms of Wess-Zumino type to restore the gauge symmetry, broken at 1-loop level. The cancellation of the anomaly, if realized by a local counterterm, indeed defines an anomaly-free theory with the appearance of an axion in the spectrum [3]. This new degree of freedom is described by a real Stückelberg field b which undergoes a local shift under the anomalous gauge symmetry.

Theories of this type have clearly a unitarity bound [4] but are consistent effective theories up to a certain scale which is given by the Stückelberg mass (M_{St}). This appears in two ways: 1) as a tree-level contribution to the mass of the anomalous gauge boson (via the Stückelberg mechanism) and as a suppression factor of the Wess-Zumino interactions ($\sim b/M_{St}FF$), where b is the Stückelberg field. Details on the construction of complete extensions of the Standard Model with one extra $U(1)$ gauge symmetry have been given in [5], to which we refer for further details.

One additional remark concerns the possible motivations in favour of these types of theories, which are not justified only within models of intersecting branes, which originally brought to define their structure [3]. Their formulation is indeed rather general and therefore they grasp the essential features of theories with anomalous gauge interactions. Thus, they can be formulated in a bottom-up approach quite straightforwardly, just using some few basic and simple requirements, first among them being, indeed, gauge invariance. Notice that the Stückelberg field is dynamical, and this forces necessarily the anomalous gauge boson to acquire a mass at tree-level via a Stückelberg mass term.

The discussion of simple models containing these essential features is contained in [6]. In principle, one could extend this construction to the supersymmetric case and also merge them into a standard gravitational framework. Indeed one may expect that these descriptions, after suitable generalizations, should grasp, at least in part, the physical features of theories with gauged supergravities (see for instance [7, 8]) which also contain axionic symmetries.

As we have mentioned, one of the open issues, from the phenomenological viewpoint, concerns the strength of the extra potential, whose structure can be predicted on the basis of gauge invariance up to an overall factor which is left, however, undetermined. In this respect one can envision various possible ranges for the size of the mass of the physical axion that emerges from the Stückelberg field. The physical (gauged) axion, called the “axi-Higgs” in [3], appears in the CP-odd sector after electroweak symmetry breaking and acquires a mass which depends on the size of the extra potential.

The first window for the mass parameter is in the few GeV range, where the axion is akin a light pseudoscalar Higgs particle, with a fast decay and a phenomenology which has been studied in [9]. A second window could correspond to a particle whose mass is in the keV/MeV region, heavy enough not to be produced at the center of the sun, thereby satisfying the current bounds from experiments such as CAST, which look directly for axions coming from the sun. A third possibility is a particle of a mass in the milli-eV region, which coincides with the expected mass range for a traditional PQ axion. In this case, the analysis of the cosmological implications of this particle and of the sequential

mechanisms of misalignments which characterize its mass have been studied in [10].

The phase-dependent potential

One of the most significant features of axion models is in the appearance of a phase-dependent (or axion-dependent) potential which is periodic in the axion field and which can be inferred just on the basis of symmetry [3]. The simplest realization of models characterized by this feature involves gauge theories containing two Higgs doublets, that we are going to summarize. The model originally studied in [3, 5] contains a single extra anomalous $U(1)$ plus an axion b (a real pseudoscalar) to enforce cancellation of the anomaly.

As in previous works [5], the scalar sector of the anomalous abelian models that we are interested in is characterized by an electroweak potential involving, in the simplest formulation, two Higgs doublets $V_{PQ}(H_u, H_d)$ plus one extra contribution (the extra potential mentioned above), denoted as $V_{\mathcal{PQ}}(H_u, H_d, b)$ or V' , [3] which mixes the Higgs sector with the Stückelberg axion b , needed for the restoration of the gauge invariance of the effective Lagrangian

$$V = V_{PQ}(H_u, H_d) + V_{\mathcal{PQ}}(H_u, H_d, b). \quad (1)$$

The appearance of the physical axion in the spectrum of the model takes place after that the phase-dependent terms, here assumed to be of non-perturbative origin and generated at the electroweak phase transition, find their way in the dynamics of the model and induce a curvature on the scalar potential. To better illustrate this point, we begin our analysis by turning to the ordinary potential of 2 Higgs doublets,

$$\begin{aligned} V_{PQ} = & \mu_u^2 H_u^\dagger H_u + \mu_d^2 H_d^\dagger H_d + \lambda_{uu}(H_u^\dagger H_u)^2 + \lambda_{dd}(H_d^\dagger H_d)^2 \\ & - 2\lambda_{ud}(H_u^\dagger H_u)(H_d^\dagger H_d) + 2\lambda'_{ud}|H_u^T \tau_2 H_d|^2 \end{aligned} \quad (2)$$

to which we add a second term

$$\begin{aligned} V_{\mathcal{PQ}} = & \lambda_0(H_u^\dagger H_d e^{-ig_B(q_u-q_d)\frac{b}{2M}}) + \lambda_1(H_u^\dagger H_d e^{-ig_B(q_u-q_d)\frac{b}{2M}})^2 \\ & + \lambda_2(H_u^\dagger H_u)(H_d^\dagger H_d e^{-ig_B(q_u-q_d)\frac{b}{2M}}) + \\ & \lambda_3(H_d^\dagger H_d)(H_u^\dagger H_d e^{-ig_B(q_u-q_d)\frac{b}{2M}}) + \text{h.c..} \end{aligned} \quad (3)$$

These terms, as we have mentioned, are allowed by the symmetry of the model and are parameterized by one dimensionful (λ_0) and three dimensionless constants ($\lambda_1, \lambda_2, \lambda_3$). They are assumed to be generated at the electroweak phase transition. The physical axion χ emerges as a linear combination of the phases of the various terms, which are either due to the CP-odd components of the Higgs sector or to the Stückelberg field b . A careful analysis of the the CP-odd sector shows that we can construct the orthogonal matrix O^χ that rotates the Stückelberg field and the CP-odd phases of the two Higgs doublets into

the mass eigenstates (χ, G_1^0, G_2^0)

$$\begin{pmatrix} \text{Im}H_u^0 \\ \text{Im}H_d^0 \\ b \end{pmatrix} = O^\chi \begin{pmatrix} \chi \\ G_1^0 \\ G_2^0 \end{pmatrix} \quad (4)$$

of the same sector. The mass matrix of this sector exhibits two zero eigenvalues corresponding to the Goldstone modes G_1^0, G_2^0 and a nonzero eigenvalue, that corresponds to the physical axion field χ , with a mass given by

$$m_\chi^2 = \frac{2v_u v_d}{\sigma_\chi^2} (\bar{\lambda}_0 v^2 + \lambda_2 v_d^2 + \lambda_3 v_u^2 + 4\lambda_1 v_u v_d) \approx \lambda v^2 \quad (5)$$

(with $\lambda_0 = \bar{\lambda}_0 v^2$). Notice that one can rewrite the extra potential in the form[11]

$$V' = 4v_u v_d (\lambda_2 v_d^2 + \lambda_3 v_u^2 + \lambda_0) \cos\left(\frac{\chi}{\sigma_\chi}\right) + 2\lambda_1 v_u^2 v_d^2 \cos\left(2\frac{\chi}{\sigma_\chi}\right), \quad (6)$$

with χ a gauge invariant degree of freedom. As we have remarked, this state is extracted from the CP-odd sector after a careful study of the Goldstone modes of the theory in the broken electroweak phase. In (6) σ_χ is of the order of the electroweak scale and the ratio χ/σ_χ is clearly an angle of misalignment. From a simple phenomenological point of view, given the presence of a free parameter in the characterization of the extra potential, one can envision several possible scenarios. In [11] it has been assumed that this potential can be generated non perturbatively by some instanton interaction, and as such its strength ($\sim \lambda$) should be strongly suppressed, but obviously there are other options. The one which is more interesting for LHC studies involves a light axion which is Higgs-like, but with a mass that covers the few GeV region. In the next section we will briefly explore this possibility, showing some predictions for the main channels of production and decay of this particle at the new collider.

AXI-HIGGS DECAY AND PRODUCTION AT HADRON COLLIDERS

We show in Fig. (1) plots which illustrate the behaviour of the (inclusive) decay branching ratios of the axi-Higgs into quarks and leptons as a function of the mass of the physical axion, obtained by varying the charge assignments of the model. The enhancement of the lepton decay channels for a light axion mass between 4 and 8 GeV - respect to the quark channel - is quite evident from this plot, and the results are rather stable respect to the variations induced by the different charge assignments of the model. These have been parameterized by the function $f(q_{Q_L}^B, q_{u_R}^B, \Delta q^B)$ of three variables. These are the charges of the left and right-handed quarks under the anomalous $U(1)_B$ gauge group ($q_{Q_L}^B, q_{u_R}^B$) while Δq^B denotes the difference in the charges of the two Higgses under the same gauge group. The remaining charges of the model are fixed by anomaly cancellation and are described in [9]. Notice that the differences among the various charge assignments are smaller than 10^{-3} .

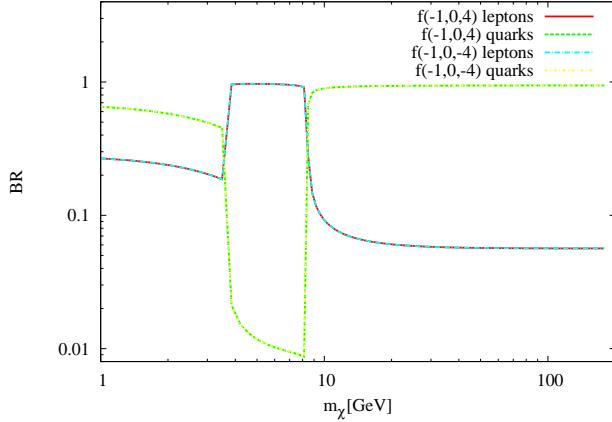


FIGURE 1. Study of the leptonic and the quarks branching ratios of the axi-Higgs. We analyze the dependence on the function $f(q_{Q_L}^B, q_{u_R}^B, \Delta q^B)$.

The study of the production of the axi-Higgs at hadron colliders is particularly interesting, especially for the possibility of having sizeable branching ratios of the two CP-even Higgs Higgs H_0 and h_0 into final state axions.

The free parameters of the scalar potential can be identified by the coefficients $(\lambda_{uu}, \lambda_{dd}, \lambda_{ud}, \lambda'_{ud})$ that are contained in the PQ potential and by $(b_1, \lambda_1, \lambda_2, \lambda_3)$, that are contained in the PQ -breaking potential. The other free parameters are the ratio of the Higgs vevs, identified with $\tan\beta$, the Stückelberg mass M_{St} and the coupling constant g_B .

We start our analysis by considering a scenario in which the mass of the Z boson is exactly reproduced at $M_Z = 91.1876$ GeV and the bounds on the mass of the extra Z' are required to be compatible with the current Tevatron data. These conditions can be obtained by fixing the value of the anomalous coupling $g_B \approx 0.1$, the value of $v_u \approx 246$ GeV, the value of the Stückelberg mass in the TeV range and $\tan\beta = 40$. These requirements induce also a small mixing parameter between Z and Z' (below 10^{-3}), which is also in agreement with current data. Thus, the mass of the particles of the scalar sector are identified by the eight parameters listed above. The value of the mass of the axi-Higgs is completely governed by the PQ -breaking sector of the potential. The other parameters enter in the definition of the mass of the two neutral Higgs and the corresponding mass eigenvalues are found to be very sensitive to the selection of these parameters. In our case these have been chosen as $\{\lambda_1, \lambda_2, \lambda_3, b_1, \lambda_{uu}, \lambda_{dd}, \lambda_{ud}\} = \{-9 \cdot 10^{-5}, -1 \cdot 10^{-6}, -1 \cdot 10^{-5}, 5 \cdot 10^{-3}, 6 \cdot 10^{-2}, 5, 0.9\}$, with the masses of the CP-even and of the CP-odd sectors given by $\{m_{H_0} \approx 122, m_{h_0} \approx 15, m_\chi \approx 5\}$ (GeV).

In Figs. 3 we show the plots of the total cross section at leading order (LO) - at the LHC and at the Tevatron respectively - for the production of the axion and the CP-even H_0, h_0 Higgs, and the corresponding plots for the SM Higgs. Notice that the result shows a rather sharp rise of the production cross section as the axion mass gets lighter. This is larger by a factor of 10 compared to the case of other CP-even scalars. A similar rise is found also for the CP-odd sector in 2 Higgs doublet models, being a feature typical of

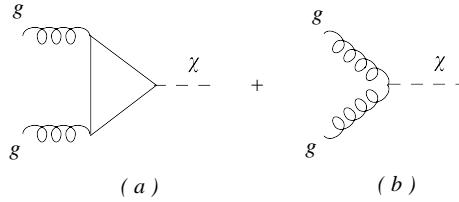


FIGURE 2. The two contributions to the $gg \rightarrow \chi$ production channel.

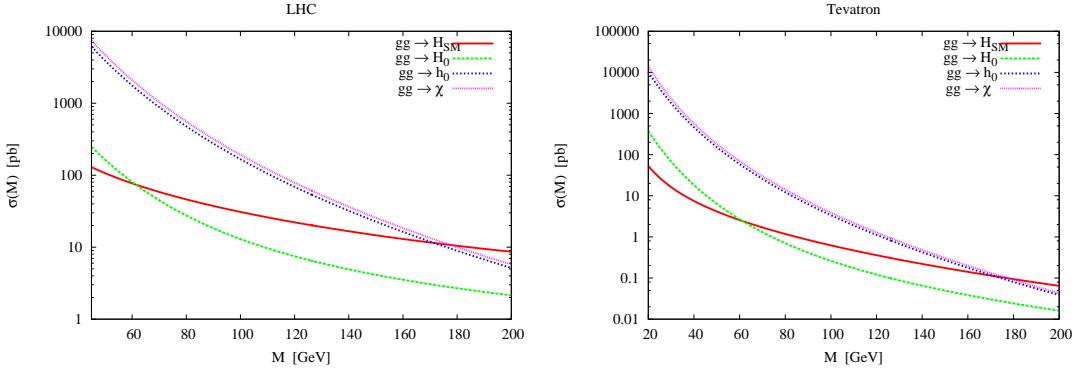


FIGURE 3. Cross section for the production of the two Higgs h_0 and H_0 and the axi-Higgs via gluon-gluon fusion at LO at the LHC (left panel) and at the Tevatron (right panel).

the CP-odd Higgs sector.

Axion plus photon production

The diagrams responsible for associated production of a gauged axion and a photon are shown in Fig. 4. We show instead in Fig. 5 a plot of the cross section for the production of an axion and one photon at the LHC as a function of the mass of χ . The mass dependence of the result is quite small, except at larger mass value of χ , in a region where it is Higgs-like. For an ultralight axion, instead, the value of the cross section is around 10^{-2} pb. We have shown the contribution from the triangle and the Wess-Zumino terms combined together and separately, in order to show the dominance of one channel respect to the other. The Wess-Zumino term is indeed strongly suppressed (by a factor of 10^{10}) respect to the fermion loop.

Multi axion production

One of the peculiarities of a light axion-like particle is its possibility to generate cascade decays with multi-lepton final states which become more sizeable especially for a mass of χ in the GeV range. For m_χ around few GeV's the largest contribution to

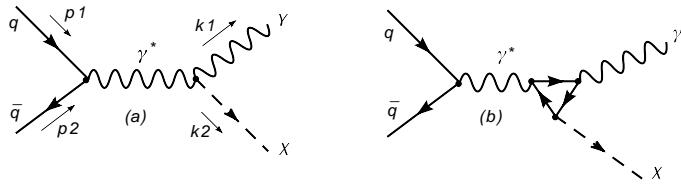


FIGURE 4. Associated production channel for a single gauged axion plus a photon

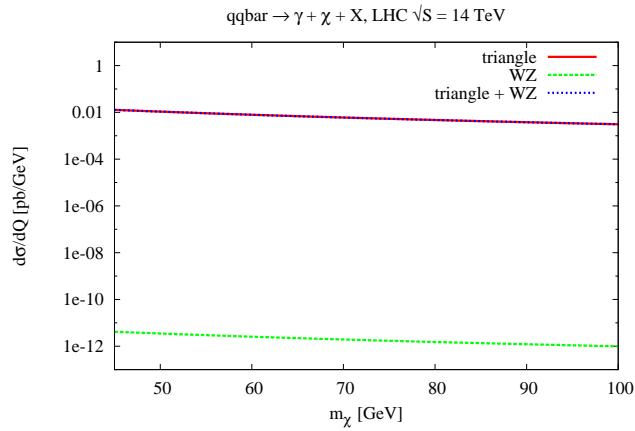


FIGURE 5. Invariant mass distribution for the associated production of an axion plus one photon at the LHC.

the decay branching ratio comes from the lepton channel, and for this reason we have investigated this particular interval in parameter space.

The sizeable values of the invariant mass distributions for multi-axions in the final state are related to the large production cross sections which are typical of pseudoscalar channels, one of the reasons being the large values of the reduced couplings - normalized to the SM ones - of the trilinear interactions of the scalars. The leading contribution to the production cross section comes from the fermion loop graph with a final state axion. In the model each contribution is accompanied by the corresponding WZ counterterm, which is suppressed by a factor of 10^5 compared to the loop graph (see Fig. 2).

Channels involving several final state axions can be built rather easily. For instance, the simplest process involves a $gg - h_0$ (two gluon g) production channel combined with the $h_0 - \chi\chi$ vertex. In this case the WZ counterterm is absent. A similar process is the $gg - \chi$ triangle vertex, followed by the $\chi\chi h_0$ vertex, which gives the combination of a χ and of a CP-even Higgs (h_0) in the final state. In this case the channel is accompanied by a WZ term $gg - \chi$ describing the direct interaction of the two gluons of the initial state with the axion.

Cascading channels can be easily obtained by combining trilinear ($\chi\chi h_0$) and quadrilinear (χ^4) vertices, which are more involved. The results of this study are shown in Fig. 6 for the Tevatron and the LHC respectively. The plots presented in the two figures show sizeable rates which become large on the Higgs (H_0) resonance, chosen to be at 120 GeV. At the LHC the peak value of the cross section for $pp \rightarrow \chi\chi$, mediated by

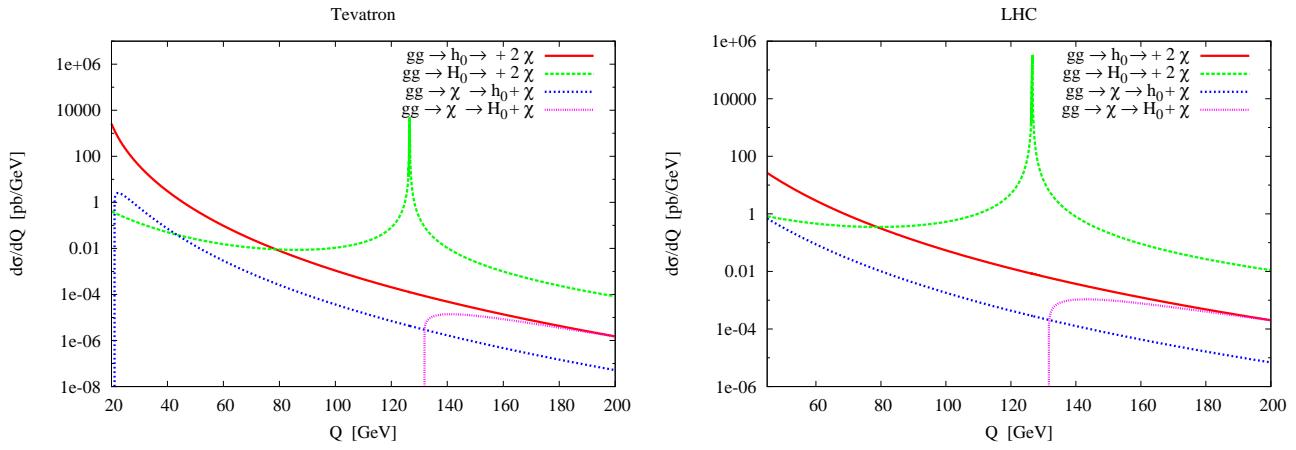


FIGURE 6. $gg \rightarrow 2\text{-scalar}$ reactions mediated by trilinear vertices.

the H_0 is larger by a factor of about $10 - 100$ compared to the Tevatron and would be significant for future searches.

CONCLUSIONS

Axions derived from models containing anomalous extra $U(1)$ symmetries, if found at the LHC, would be of paramount theoretical importance. The search for this particle remains strongly tied to the possibility of uncovering an anomalous gauge boson at ATLAS and CMS in the next years and to the study of the trilinear gauge interactions [12]. For an axion which is Higgs-like, the phenomenology is rather interesting and is characterized by sizeable production rates.

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